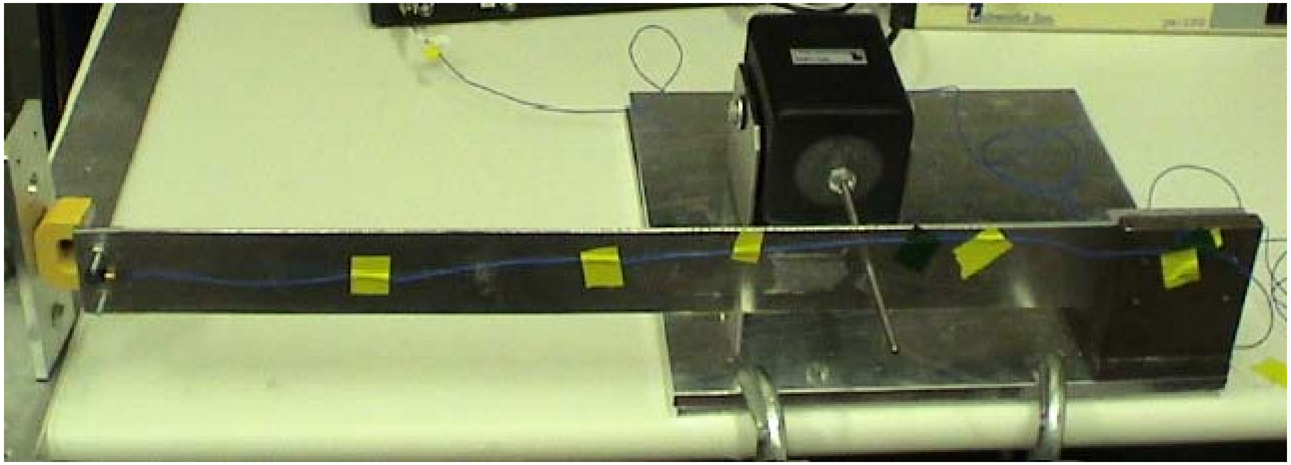
Shaker Control in the Presence of Nonlinearities



Kelly Brinkley, University of Denver

Steve Holman, Montana State University

Kai Yu, Stanford University

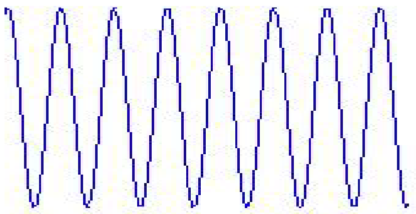
Mentor: Matt Bement, LANL Staff

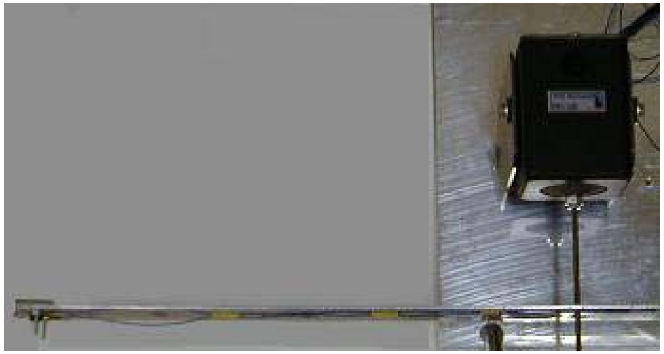
Motivation

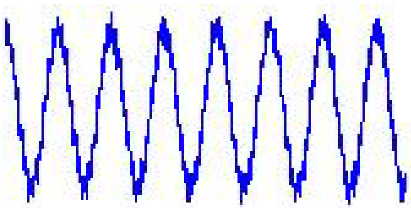
- Shaker control systems are required to remove shaker dynamics and coupling effects

- Nonlinearities in a structure or environment can influence input force and measured response in a vibration or accelerated aging tests

- Desire to eliminate nonlinear effects using a shaker controller

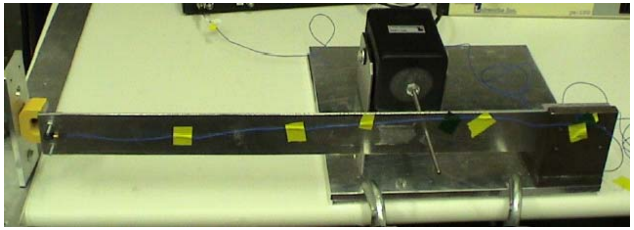


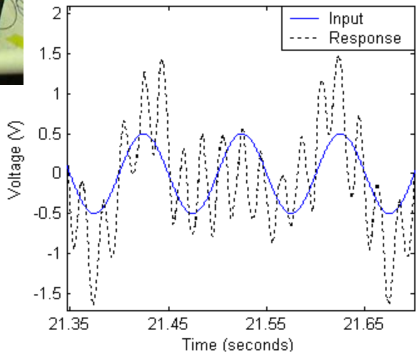




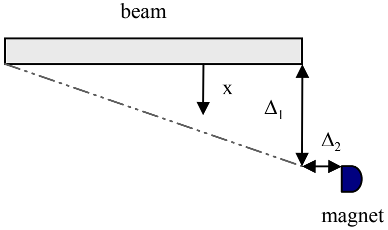
Outline

- Experimental Setup

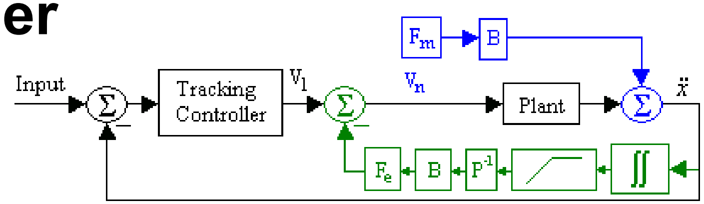




- Nonlinearity
- Modal Parameter Extraction



- Extended Kalman Filter
- Feedback Linearization Controller



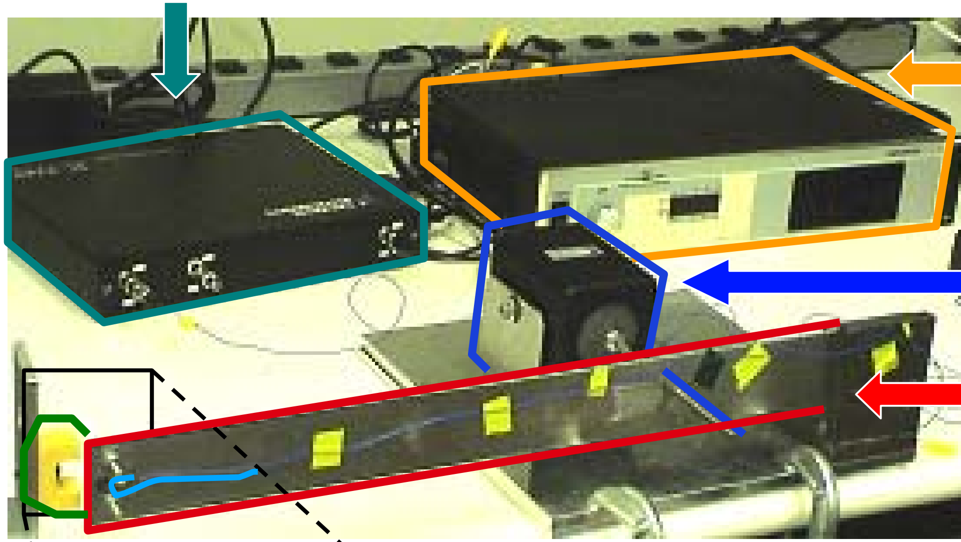
- Results

UNCLASSIFIED

Experimental Setup

PC (not pictured) containing NI PCI 6052E data acquisition card, XPC real-time OS

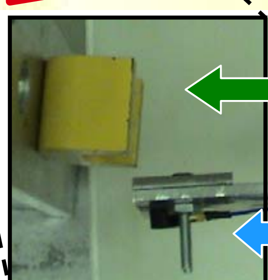
National Instruments SC-2345 Signal Conditioner



Labworks PA-138 Amplifier

Labworks ET-132-2 Shaker

Aluminum Cantilever Beam (61cm x 5.1cm x .32cm)



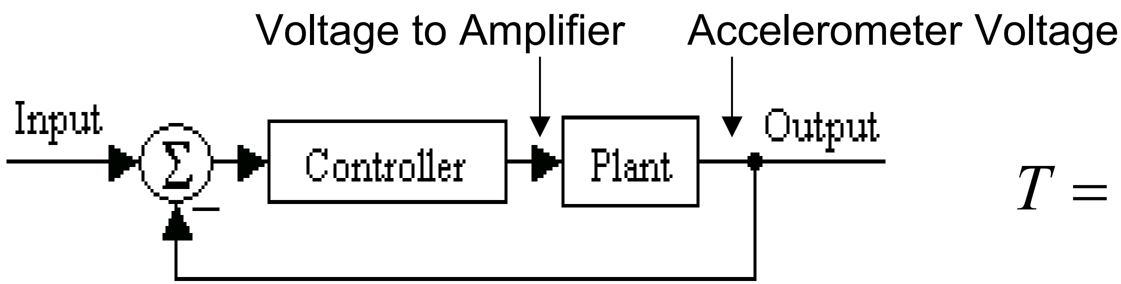
U-Magnet (2.5cm x 2.5cm x 3.7cm, characteristic gap of 1.7cm)

PCB 352A24 Accelerometer

Strategy

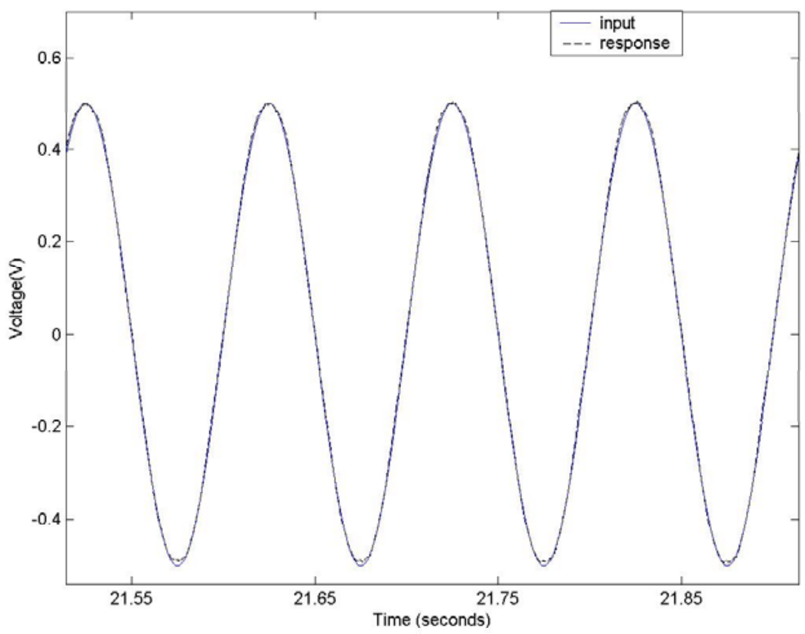
- **Design a controller to track a 0.5V amplitude, 10 Hz sinusoid without the magnet**
- **Add magnet and observe tracking with the same controller**
- **Attempt to remove nonlinearity using feedback linearization controller**
  - Use extended Kalman filter to estimate parameters
  - Obtain modal parameters for use in Kalman filter

Controls Background



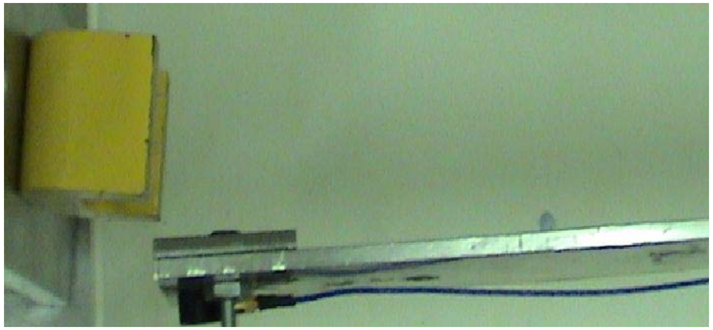
$$T = \frac{P(s)C(s)}{1 + P(s)C(s)}$$

- **Tracking controller makes the output and input waveforms the same**
- **Relatively easy for single frequency, harder for multiple frequencies**

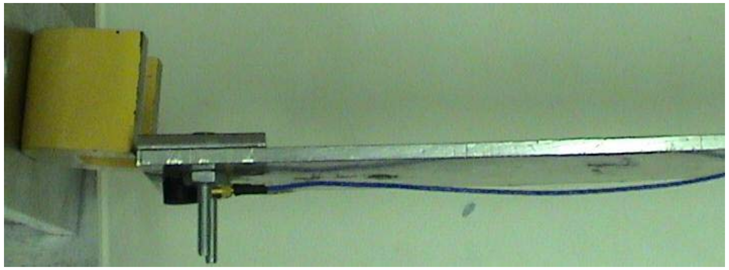


Nonlinearity – Equilibrium Points

- First equilibrium point



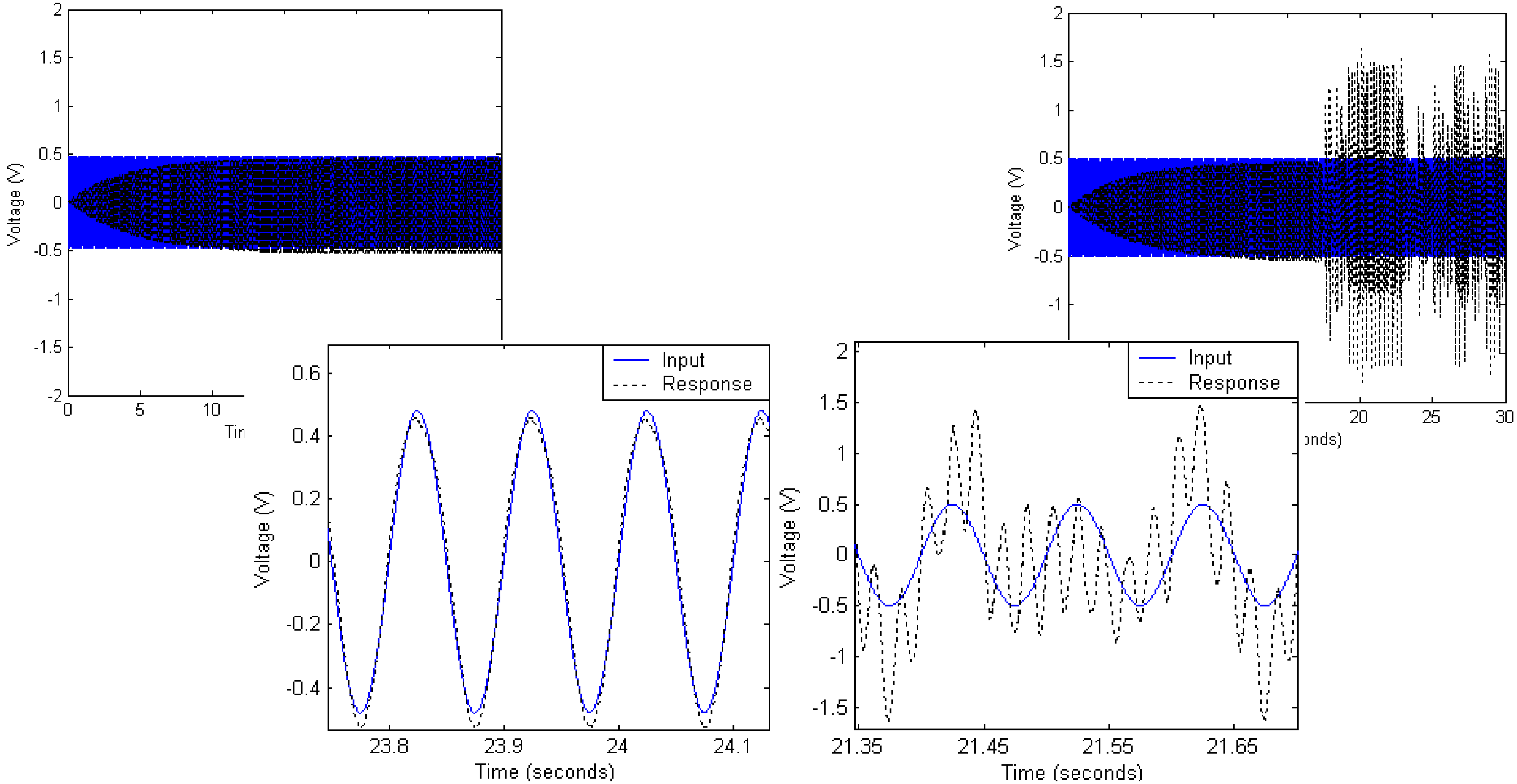
- Second equilibrium point 1.2 cm away



- Magnetic force modeled as: $$F = \frac{C}{d^3}$$

UNCLASSIFIED

Nonlinearity - Tracking



- **Tracks 0.48V sinusoid, but 0.5V sinusoid reaches a “remote, non-periodic attractor”**

Modal Parameter Extraction

- **Impact hammer test on free beam (shaker not attached) and SEREP reduction on FEA data (high fidelity)**
  - SEREP reduced mass and stiffness matrices do not require the original system mass and stiffness matrices.
  - Subsequent reduced mass and stiffness matrices.
- **Generalized inverse of analytical modal vectors**
  - Compare to reduced matrices via generalized inverse – exact same
- **Generalized inverse of experimental modal vectors**
  - Compare – good agreement

Modal Parameter Extraction

- **Apply above procedure to true beam (shaker attached) and obtain mass, damping, and stiffness matrices to be used in extended Kalman filter**

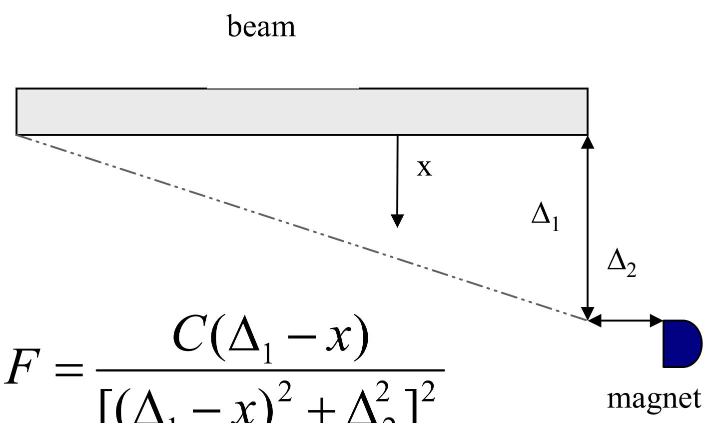
- **Comparison between analytical and experimental through MAC and POC**

Modal Assurance Criteria with Quill		
0.9947	0.0550	0.0624
0.0314	**0.9963**	0.2253
0.0785	0.0752	**0.9664**

Pseudo Orthogonality Check with Quill		
0.9977	-0.0625	0.0243
-0.0059	**-0.9978**	-0.0664
-0.1004	0.1810	**-0.9783**

Extended Kalman Filter

- **Purpose**
  - Estimate parameters of the magnetic force: C, Δ_1, and Δ_2

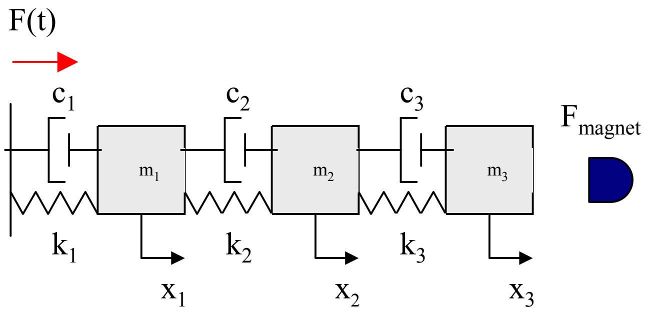


$$F = \frac{C(\Delta_1 - x)}{[(\Delta_1 - x)^2 + \Delta_2^2]^2}$$

- **Method**
  - Extended Kalman Filter (EKF) is a predictor/corrector technique
  - First estimates the state and error covariance
  - Updates estimates using the Kalman gain

Extended Kalman Filter: Implementation

- Magnetic force $$F = \frac{C(\Delta_1 - x_3)}{[(\Delta_1 - x_3)^2 + \Delta_2^2]^2}$$
- Assume a 3 degree of freedom model



- Verify convergence in the model with simulations
- Incorporate experimental displacement and modal parameters into the filter
- Verify filter predictions by determining equilibrium points

Results: Extended Kalman Filter

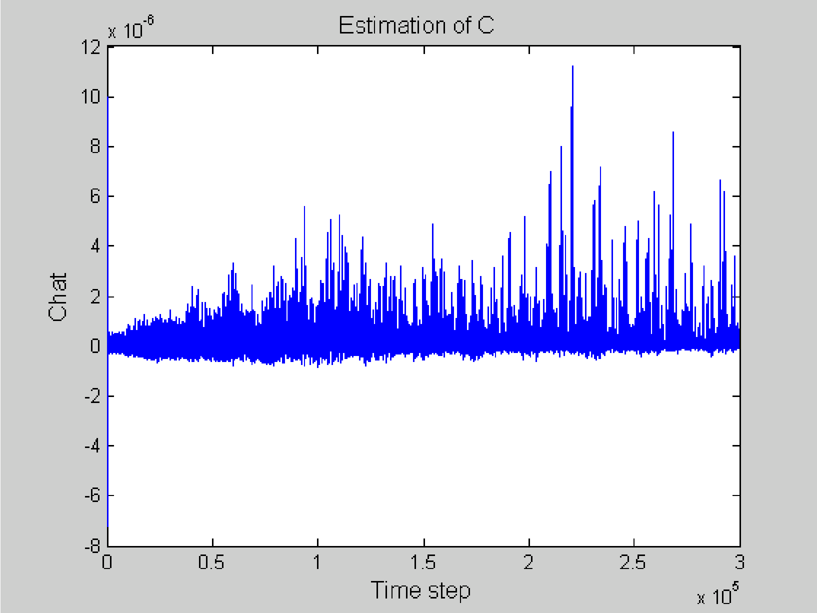
- **Simulated**

  Converges for C, Δ_1, and Δ_2

  - Initial estimates must be within ±50% of actual parameter values

- **Experimental**

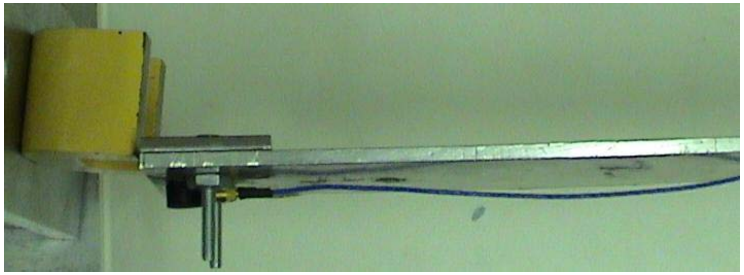
  - C oscillates in the range of $\pm 10^{-5}$ N•m^3
  - Δ_1 and Δ_2 do not converge, but stay in the same order of magnitude

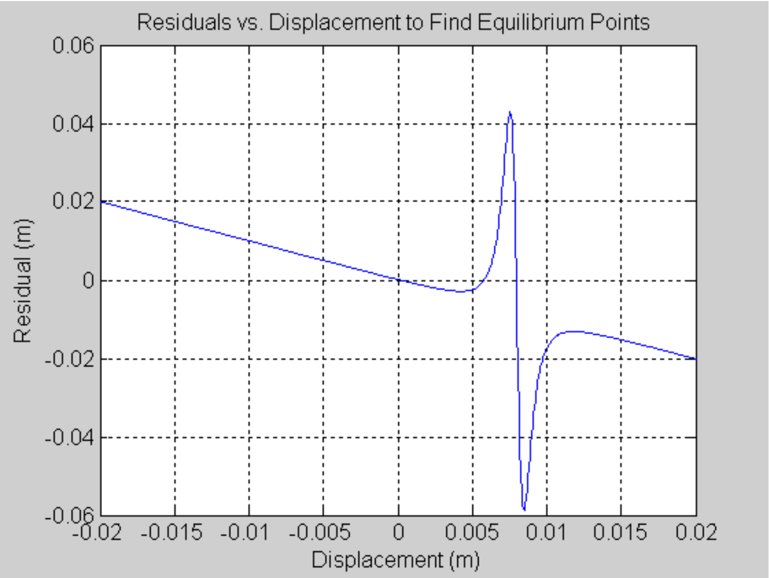


UNCLASSIFIED

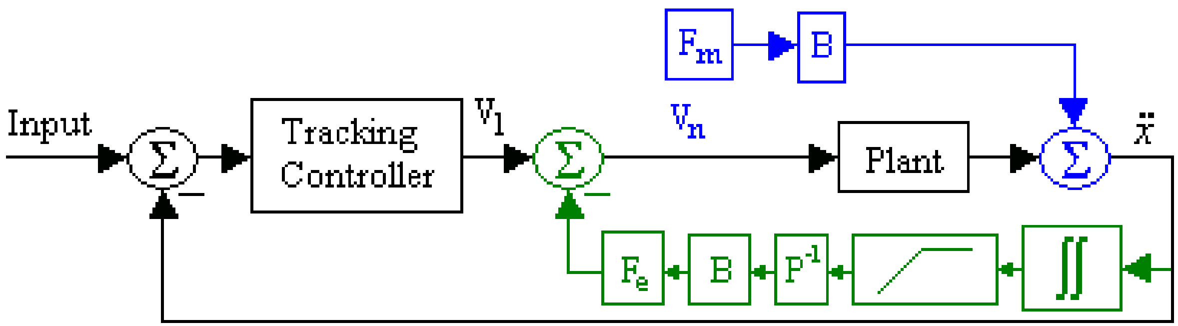
Results: Model Verification

- **Equilibrium Points**
  - For C = 1.05e-7, Δ_1 = 0.0082m, and Δ_2 = 0.0008m, only one equilibrium point at 0.0080m
  - Decrease C to 1e-8 to find three points at 0.00016m, 0.0058m, and 0.0080m





Feedback Linearization Controller



Acceleration without Magnet $\quad \ddot{x} = Pv_l$

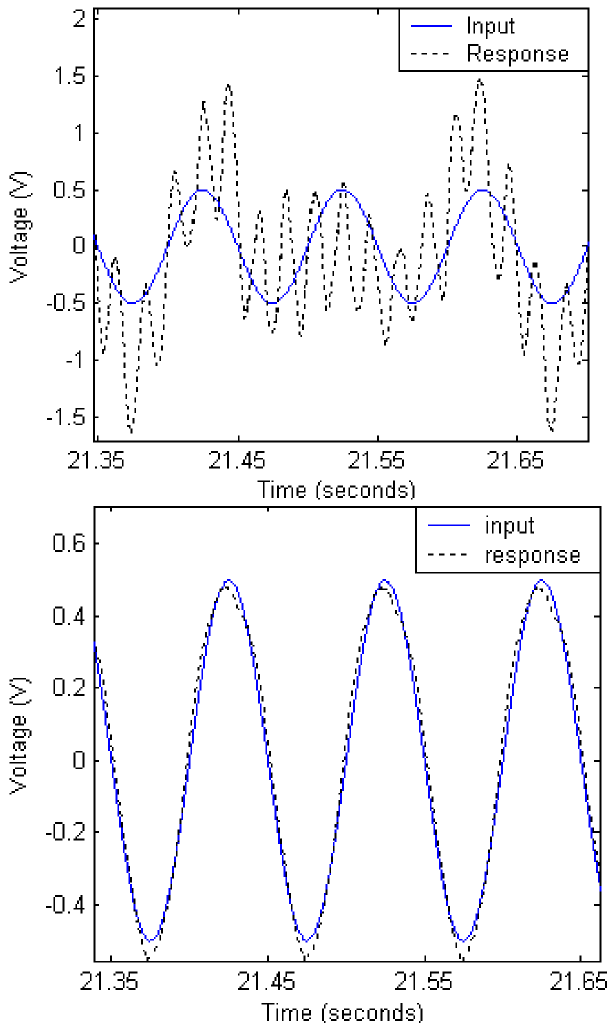
Acceleration with Magnet $\quad \ddot{x} = PV_n + BF_m(x)$

Feedback Linearization Controller $\quad V_n = v_l - P^{-1}B\,F_e(x)$

Resultant Acceleration $\quad \ddot{x} = Pv_l$

Results: Feedback Linearization Controller

- **Tracking significantly improved at 0.5V amplitude sinusoid**
- **Controller did not adversely affect tracking of lower amplitudes**
- **At higher amplitudes, required voltage exceeded capabilities of D/A channel**



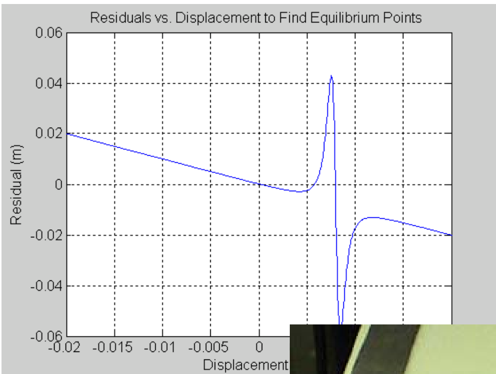
Summary

- **We compensated for the nonlinearity**
- **Extended Kalman filter and equilibrium point check provided acceptable starting point for feedback linearization controller**
- **Recommendations for future research:**
  - Apply technique to a more complex structure
  - Apply technique to a less well-defined nonlinearity
  - Create control to track over frequency range and test feedback linearization controller

Acknowledgements

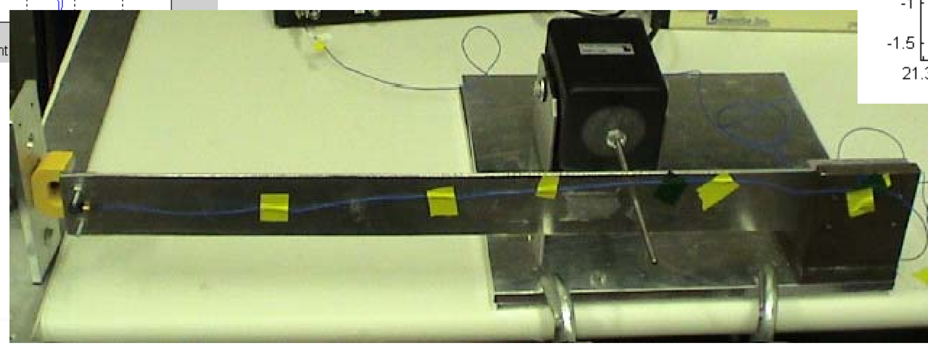
- **The completion of this project is largely due to the contribution and help from the following:**
  - Dr. Matt Bement, for his guidance on all aspects of this project
  - Dr. Peter Avitabile, for his help with data reduction, correlation, system matrix estimation and software
  - Dr. Charles Farrar, for enabling this project to exist by hosting and managing the Dynamics Summer School
  - Department of Energy and the ESA Division, for providing funding for the Dynamics Summer School
  - Vibrant Technologies
  - The Mathworks, Inc.
  - Dynamic Design Solutions
  - Hibbitt, Karlsson, and Sorensen, Inc.

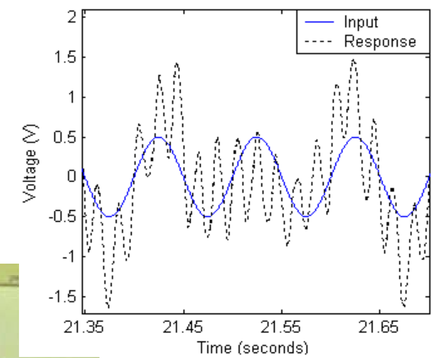
Questions and Comments



Extended Kalman Filter

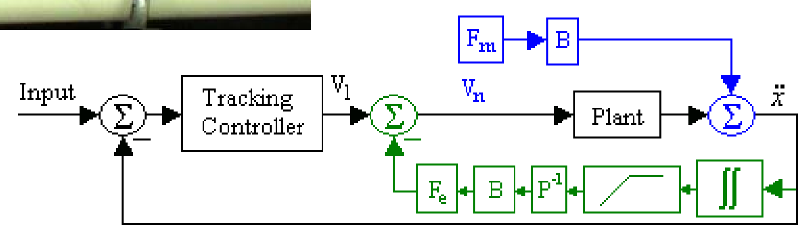
Experimental Setup





Nonlinearity

Modal Parameter Extraction



Feedback Linearization Controller